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Feasibility Study of Enhanced Combustion via Improved Wood Stove Firebox Design

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FEASIBILITY STUDY OF ENHANCED COMBUSTION VIA IMPROVED WOOD STOVE FIREBOX DESIGN

by

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16. ABSTRACT The report gives results of an examination of materials that might be used to line the firebox of a wood burning stove to produce more uniform and complete combustion. (Emissions from incomplete combustion in wood burning stoves are becoming an increasing environmental problem.) Although many materials were considered initially, refractory materials appear to possess the qualities desired relative to heat transfer, resistance to the firebox environment, availability, and cost. Further investigation of specific refractory materials has been carried out, resulting in a list of material properties of potentially useful refractories and a determination of the relative costs of installed refractory. The approach used in the study was to establish the conditions for a "basic" stove, then to apply various candidate lining materials to the basic stove and analytically estimate the effect of the lining addition. Basic heat transfer calculations were used. The use of refractory materials permitted an increase in stove inner wall temperatures and an increased cool-down time for a stove. The study shows that refractory materials can aid in maintaining internal firebox temperatures above the ignition temperatures of common emissions. This would not be practical for an uninsulated stove. The study concludes that there is a need for actual tests to confirm results cited in the study.

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Pollution Heat Transfer	Pollution Control	13B 20M
Combustion Chambers	Stationary Sources	21B
Wood	Wood Stoves	11L
Stoves		13A
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ABSTRACT

Emissions from incomplete combustion in wood burning stoves are becoming an increasing environmental problem. In this study, materials were examined which might be used to line the firebox of a wood burning stove to produce more uniform and complete combustion. Although many materials were initially considered, refractory materials appear to possess the qualities desired relative to heat transfer, resistance to the firebox environment, availability, and cost. Further investigation of specific refractory materials has been carried out, resulting in a listing of material properties of potentially useful refractories and a determination of the relative costs of installed refractory. The approach used in this study was to establish the conditions for a "basic" wood stove, then to apply various candidate lining materials to the "basic" stove and analytically estimate the effect of the lining addition. Basic heat transfer calculations were used. The use of refractory materials permitted an increase in stove inner wall temperatures and an increased cooldown time for a stove. The results of this study show that refractory materials could aid in maintaining internal firebox temperatures above the ignition temperatures of common emissions. This would not be a practical operational mode for an uninsulated stove. This study also concludes that there is a need for actual testing to confirm the results cited in this study.

The expanding usage of wood burning stoves and consequent increase in overall emissions has become an area of environmental concern. The development of potentially widely applicable methods to reduce wood stove emissions is an appropriate and necessary approach towards mitigating the wood stove emissions problem.

This report provides a design methodology which may, within the limits of its narrow focus, provide a useful concept towards the reduction of wood stove emissions.

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SECTION 1

INTRODUCTION

The use of residential wood burning stoves has grown considerably in recent years. As the use of these stoves has increased, so has the amount of polluting emissions. Since these stoves come in a very wide range of designs, combustion and resulting emissions can vary widely. Additionally, operational parameters can result in significantly different emission levels from the same stove design. One design approach for reducing emissions is to place material inside the firebox that can lead to more complete combustion of the wood charge and any emission constituents present. Ideally any design modification should be essentially passive; i.e., requiring little or no attention by the user. Also, due to the large numbers of existing wood burning stoves, it is desirable that any modification lend itself to the retrofit of existing stoves.

SECTION 2

CONCLUSIONS

Various types of refractory materials can be installed within a wood stove firebox. These materials can lead to temperatures at and near the refractory surface that are above the ignition temperature of many wood stove emission constituents.

A refractory lined stove will tend to have a longer cooldown period than a metal stove.

A quantification of the effectiveness of emission reductions attributable to the types of firebox designs considered herein should be determined by various testing procedures.

SECTION 3

EXISTING STOVE DESIGNS

The design of existing residential wood stoves was reviewed to ascertain the various design and operational factors that affect wood stove emissions. The major design factors included several variables: combustion chamber usage (sites), drafting design, heat transfer mechanism(s), combustion controls, and materials of construction. The operational factors included three variables: draft and flue adjustments, fuel type, and stove charging techniques. These design and operational factors are listed in Tables 3-1 and 3-2, respectively.

The observations concerning performance with reduced emissions were derived from the review of existing stove designs. The primary activity in emission reductions in wood burning stove designs is the utilization of catalytic combustors. The design incorporation and after market insertion of catalytic combustors is spurred by their relatively low cost and largely passive operation. The second observation concerns the good results that have been reported from emission tests of ceramic stoves.(1) While various wood stoves constructed from "mixed" materials (e.g., metal with stone inserts) are available, there does not seem to be an all ceramic wood burning stove currently in production in the United States.

3.1 REFERENCE

1. "Residential Wood Combustion Study, Task #5, Emission Testing," Green (Del) Associates, Inc., Woodburn, OR, Mar, 1983.

TABLE 3-1. DESIGN FACTORS IN WOOD BURNING STOVES.

COMBUSTION CHAMBER	DRAFTING	HEAT TRANSFER MECHANISM	COMBUSTION CONTROL	MATERIALS OF CONSTRUCTION
Primary	Down draft	Radiator - direct	Temperature probes	Ceramic
Primary and secondary	Up draft	radiation, convection,	Baffles	Soapstone
Catalytic	Cross draft	and conduction	Various air supplies	Steel
Combinations of above	Diagonal draft	Circulators - heat	(i.e., secondary air)	Cast iron
	S flow draft	exchangers	Blowers or fans	Firebrick
	Induced draft	Augmented - fans and	Manual damping	Combinations
	Forced draft	blowers	Automatic damping	of above

TABLE 3-2. OPERATIONAL FACTORS IN WOOD BURNING STOVES

DRAFT AND FLUE ADJUSTMENTS	FUEL TYPE	STOVE CHARGING TECHNIQUES
Manual	Wood logs	Manual
Automatic	Wood chips	Automatic
	Wood pellets	
	Sawdust	
	Kiln dried wood	
	Composite logs	

SECTION 4

RESISTANCE TO THE COMBUSTION PROCESS AND INCREASING COMBUSTION EFFICIENCY

4.1 BACKGROUND

A review of wood stove designs and operational parameters plus information concerning wood combustion provides a range of process conditions affecting stove usage. The mechanical suitability of any material utilized within the firebox for emission reduction must be evaluated relative to the process conditions. These include the resistance to several items: ranges of firebox temperatures and its heating and cooling rates, fuel constituents and the products evolved during combustion. Any materials placed within the firebox must be resistant to the combustion process and should help enhance it, while not appreciably degrading stove operation or requiring significant user attention. In the presence of sufficient oxygen, various emission constituents have defined ignition temperatures. Some of the emission constituents and their ignition temperatures are presented in Table 4-1.(1,2,3,4) If a material within the firebox can be maintained at or above these ignition temperatures, combustion can take place and will lead to more complete reduction of emissions such as carbon monoxide and hydrocarbons.

4.2 CALCULATION METHOD: BASIC STOVE

The approach used in this study was to establish the conditions for a "basic" wood stove, then to apply various candidate lining materials to the "basic" stove and analytically estimate the effect of the lining addition. The basic stove was defined as a cast iron stove with 1/4 inch (0.64 cm) wall thickness and no lining. The initial temperature of the firebox gases was assumed to be 1500°F (816°C). The room temperature was assumed to be 60°F (16°C). Three basic heat transfer equations, presented in Section 7.0, were used to establish the temperature of the stove wall surface. The first defines the amount of heat transferred (per square foot or square meter of stove wall) from the hot combustion gases to the stove wall due to radiation and convection. The second equation defines the amount of heat transferred (per square foot or square meter of stove wall) from the stove wall to the room due to radiation and convection. The last equation simply states that the heat transferred from the hot combustion gases to the stove wall and the heat transferred from the stove wall to the room must be equal. Employing these equations and appropriate heat transfer coefficients, the "basic" stove wall temperature was found to be 720°F (382°C), and the heat transferred (per square foot or square meter of stove wall) was approximately 4000 Btu/hr.ft^2 (12.6 kW/m^2). Thus, a firebox gas temperature of 1500°F (816°C), room temperature of 60°F (16°C), stove wall temperature of 720°F (382°C), and heat transfer rate of 4000 Btu/hr.ft^2 (12.6 kW/m^2) were considered to define the steady state conditions of the "basic" stove.(5,6)

TABLE 4-1. SOME COMBUSTION PRODUCTS RESULTING FROM THE BURNING OF WOOD

COMBUSTION PRODUCTS	
Carbon monoxide[a]	
Sulfur dioxide	
Nitrogen oxide	
Naphthalene[b]	examples of POM's (polycyclic organic matter)
Anthracene	
Penanthrene	
Biphenyl[c]	
Fluoranthene	
Pyrene	
Chrysene	
Benzene[d]	

a. Ignition temperature 1128 °F (609 °C)

b. Ignition temperature 898-1017 °F (481 - 547 °C)

c. Ignition temperature 1071 °F (577 °C)

d. Ignition temperature 1097 °F (592 °C)

4.3 CALCULATION METHOD: LINED STOVE

The steady state conditions for a lined stove were based on two assumptions. The heat transfer rate was assumed to be the same as for the "basic" stove. The outer wall temperature of the lined stove was assumed the same as for the unlined stove. These two assumptions assure that the heat output of the stove will not be affected by the addition of the lining material. (The consequences of this assumption are that the user may have to charge the stove more often.) Additionally, these assumptions provide a means of comparison between the "basic" stove and the lined stove. As the purpose of the stove lining is to raise inner stove wall temperatures so that more complete combustion of the emission constituents can be achieved, it is desired that the inner stove wall temperature be at or above the ignition temperatures of the emission constituents. Referring to Table 4-1 it is seen that carbon monoxide has the highest indicated ignition temperature, which is 1128^{o}F (609^{o}C). In an effort to compensate for some inefficiencies, an inner wall temperature of 1200^{o}F (649^{o}C) was chosen. Using these initial conditions, appropriate heat transfer coefficients, and four basic heat transfer equations, the thickness of the lining material, which can vary from material to material, and the temperature of the firebox gases necessary to support these conditions can be found. It should be noted that the equations used for the lined stove differ slightly from those used for the "basic" stove. Briefly, the first equation (Section 7.0, Eq. 4) for the lined stove represents the heat transferred (per square foot or square meter of stove wall) from the hot combustion gases to the inner stove wall due to radiation and convection plus the heat stored in the insulated (lined) wall. The second equation (Eq. 5) represents the heat conducted through the lined stove wall. The third equation (Eq. 6) is for the heat transferred (per square foot or square meter of stove wall) from the outer stove wall to the room due to radiation and convection. The last equation (Eq. 7) states that the heat transferred from the hot combustion gases to the inner stove wall, the heat conducted through the stove wall, and the heat transferred from the outer stove wall to the room are equal.

4.4 CALCULATION METHOD: COOLDOWN

Once the steady state conditions for both the stove models were established, the cooldown properties of the stoves were determined. The cooldown of the stoves was assumed to be an exponential function.(7) Using the corresponding steady state firebox gas temperature as the initial temperature and estimating a final firebox gas temperature at some later time, cooldown profiles for the "basic" stove and the lined stove can be generated. An example of the calculation methodology used is presented in Section 7.0 for medium duty firebrick lining.

4.5 CALCULATION METHOD: ANALYTICAL ACCURACY

The use of this calculation technique should be qualified. These calculations are based on some estimations and simplifications which allowed them to be performed on a hand held scientific calculator. Several values known to vary slightly with temperature were set at constant values, i. e., conductivity, conductance, and emissivity of cast iron. The firebox gases were modeled as a mixture of CO_2 and water vapor which is a common assumption for these types of calculations.(8) The heat transfer coefficients for this mixture are published in graphical format which, therefore, may have introduced inaccuracies. Introduction of error from sources such as these can be limited by use of a larger computer which is able to store tabular data and recall appropriate values for each temperature increment. Additionally, initial temperature conditions were assumed values. The intent of this study was not to perfectly describe the heat transfer behavior of a wood burning stove but rather to analytically estimate various stove operational conditions for comparative purposes. Actual testing of various wood stoves would, of course, be helpful in verifying or refining the assumed values used.

4.6 REFERENCES

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SECTION 5

CANDIDATE MATERIALS FOR INCLUSION IN THE FIREBOX

Various types of ceramics, refractories, insulating materials plus metallics, and even consumable materials were considered as candidate materials for inclusion in a wood stove firebox. These materials were evaluated for their ability to resist the process environment and to enhance combustion by the methodology described previously. The generic types of materials surveyed are listed in Table 5-1, together with comments about process resistance factors and the potential effects on combustion. Additional factors such as cost and ease of fabrication were considered during the evaluation of the various candidate materials. All materials were assumed to be added within the firebox of a basic cast iron wood stove. Standard heat transfer calculation techniques were used as described previously to determine if a candidate material could enhance the combustion process.

Based on the heat transfer calculation results and resistance considerations, refractory type materials were determined to be the most potentially viable materials for inclusion within the firebox. Table 5-2 provides a listing of important material properties for refractory-type materials. Figure 5-1 shows the effects of various thicknesses of typical refractory type materials on stove inside wall temperatures. The results of the heat transfer calculations indicate that a relatively thin section of common medium duty firebrick, for example, placed at the firebox wall, can be maintained at a temperature during steady state operation that is above the ignition temperature of several common emission constituents. The brick lining will also increase the duration of useful heat output during stove cooldown, e.g., during overnight use (see Figure 5-2). For refractory lined stoves, an inside wall temperature of 1200°F (649°C) was selected (along with an outside wall temperature of 720°F (382°C)) as an effective temperature relative to emissions ignition temperatures. The required wall thicknesses of the various refractory materials were calculated based on these assumed temperatures. These wall thicknesses are presented in Table 5-3.

Because of concerns about fouling, mechanical damage and potential overheating, catalytic materials may only be practical at or downstream of the firebox exit. Due to the dependence/variability of combustor temperatures on process conditions, catalytic combustors were not amenable to the calculation methodology utilized, and were, therefore, not considered further in this study.

Depending on stove configuration, the retrofitting with refractory linings could be difficult. Composite firebox walls, consisting of more than two materials, have not been evaluated. The heat transfer calculation methodology utilized herein would also be applicable to such designs. Auxiliary heat removal methods such as heat exchangers or fins were also not considered in the calculations.

TABLE 5-1. CANDIDATE MATERIALS

MATERIAL	COMMENTS
METALS	GENERAL: Very high heat conductivity, face temperatures may not promote combustion at or near surface.
Ferrous	
Steels/cast irons	Not resistant to peak bed temperatures.
Alloy steels	
Stainless steels	
Non-ferrous	
Aluminum alloys	Not resistant to peak bed temperatures.
Copper alloys	
Nickel/cobalt-based	Expensive.
Refractory metals (Mo, W, Cb, Ta)	Expensive.
Titanium alloys	Expensive.
Lead alloys	Not resistant to peak bed temperatures.
Magnesium alloys	Not resistant to peak bed temperatures.
Zinc alloys	Not resistant to peak bed temperatures.
Tin alloys	Not resistant to peak bed temperatures.
CERAMICS/REFRACTORIES	
Alumina	
Alumina/silica	
Silica	
Basic (MgO) (Cr_2O_3)	
Zirconia	Expensive.
Carbides/nitrides (SiC, B_4C, TiN)	Expensive.
Combustibles	Not resistant to process, not passive.
Catalytics	May overheat or foul in firebox environment.

TABLE 5-2. REFRACTORY MATERIAL PROPERTIES

MATERIAL (TRADENAME)	COMPOSITION (A/S/)		CONDUCTIVITY @ 1000° F (538°C)	DENSITY LB/FT^3 (kg/m^3)
BRICKS				
MDFB	34/59		0.65 (7.7×10^{-3})	127 (2035)
HDFB A	39/56		0.75 (8.9×10^{-3})	136 (2179)
HDFB B	45/52		1.33 (1.6×10^{-2})	139 (2227)
Mullite	69/26		1.10 (1.3×10^{-2})	144 (2307)
Alumina	90/10		1.90 (2.3×10^{-2})	183 (2932)
Alumina	99+/-		2.63 (3.1×10^{-2})	196 (3140)
Silica	-/96		0.81 (9.6×10^{-3})	115 (1842)
Vitrified Silica	-/99		0.58 (6.9×10^{-3})	118 (1890)
Basic	11/-	50 MgO 16 Cr_2O_3	1.75 (2.1×10^{-2})	193 (3092)
Zircon	-/33	67 ZrO_2	1.47 (1.7×10^{-2})	235 (3765)
Silicon Carbide	-/-	90 + SiC	10.17 (1.2×10^{-1})	166 (2659)

(continued)

[NB: NOTES APPEAR AT END OF TABLE.]

TABLE 5-2. (continued)

MATERIAL (TRADENAME)	COMPOSITION (A/S/)	CONDUCTIVITY @ 1000° F (538°C)	DENSITY LB/FT^3 (kg/m^3)
K23 IFB	39/44	0.11 (1.3×10^{-3})	31 (497)
K26 IFB	40/55	0.18 (2.1×10^{-3})	46 (737
K28 IFB	46/52	0.18 (2.1×10^{-3})	48 (769)
K30 IFB	46/52	0.20 (2.4×10^{-3})	51 (817)
K3000 IFB	64/34	0.20 (2.4×10^{-3})	58 (929)
Dense IFB	71/21	0.49 (5.8×10^{-3})	82 (1314)
CASTABLES			
Visil (1)	7/71	0.38 (4.5×10^{-3})	118 (1890)
Harchrome (1)	34/-$^{43Cr2O3}_{17\ MgO}$	0.58 (6.9×10^{-3})	156 (2499)
Keocrete B (2)	38/46	0.37 (4.4×10^{-3})	72 (1153)
KS-4 (3)	42/40	0.34 (4.0×10^{-3})	72 (1153)
Kast-set (3)	43/41	0.36 (4.3×10^{-3})	72 (1153)

(continued)

[NB: NOTES APPEAR AT END OF TABLE.]

TABLE 5-2. (continued)

MATERIAL (TRADENAME)	COMPOSITION (A/S/)	CONDUCTIVITY @ 1000° F (538°C)	DENSITY LB/FT^3 (kg/m^3)
HW Super Castable (1)	45/43	0.54 (6.5×10^{-3})	1122 (1954)
Kascrete 28LI (2)	49/42	0.52 (6.2×10^{-3})	126 (2019)
LW26 (1)	53/37	0.09 (1.1×10^{-3})	55 (881)
Hi Alumina (1)	62/30	0.67 (7.9×10^{-3})	139 (2227)
Alusa (1)	73/21	0.86 (1.0×10^{-2})	149 (2387)
Castolast G (1)	94/-	0.99 (1.2×10^{-2})	170 (2723)

NOTES:

Composition A/S/ = Alumina (Al_2O_3) / Silica (SiO_2)/other

Conductivity units = BTU ft/hr ft^2 °F (W/m^oC)

MDFB = Medium-duty firebrick

HDFB = Heavy-duty firebrick

IFB = Insulating firebrick

(1) Harbison Walker Company
(2) Babcock & Wilcox - Refractories Division
(3) A. P. Green Company

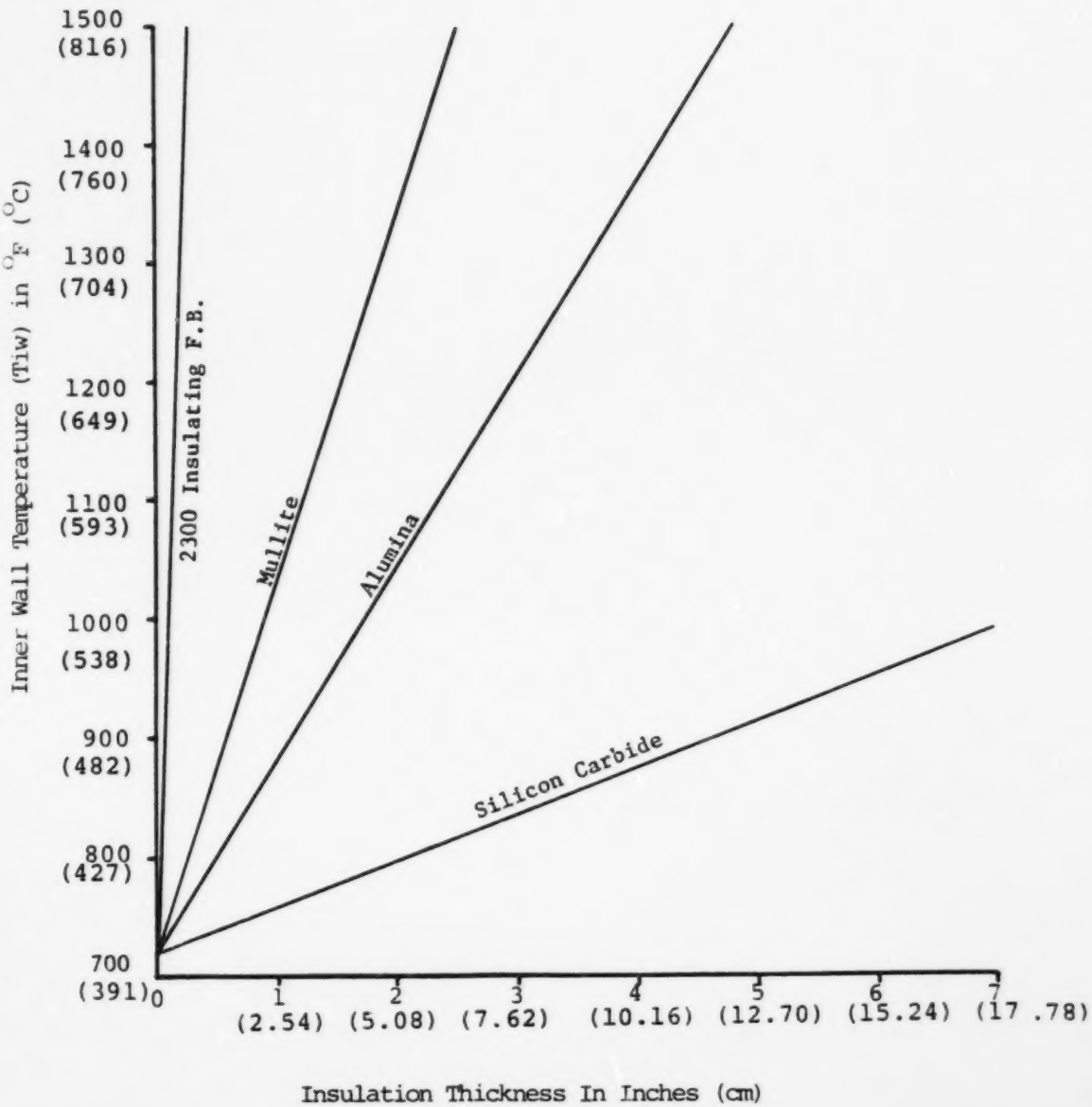

Figure 5-1. Inner Wall Temperature Versus Insulation Thickness.

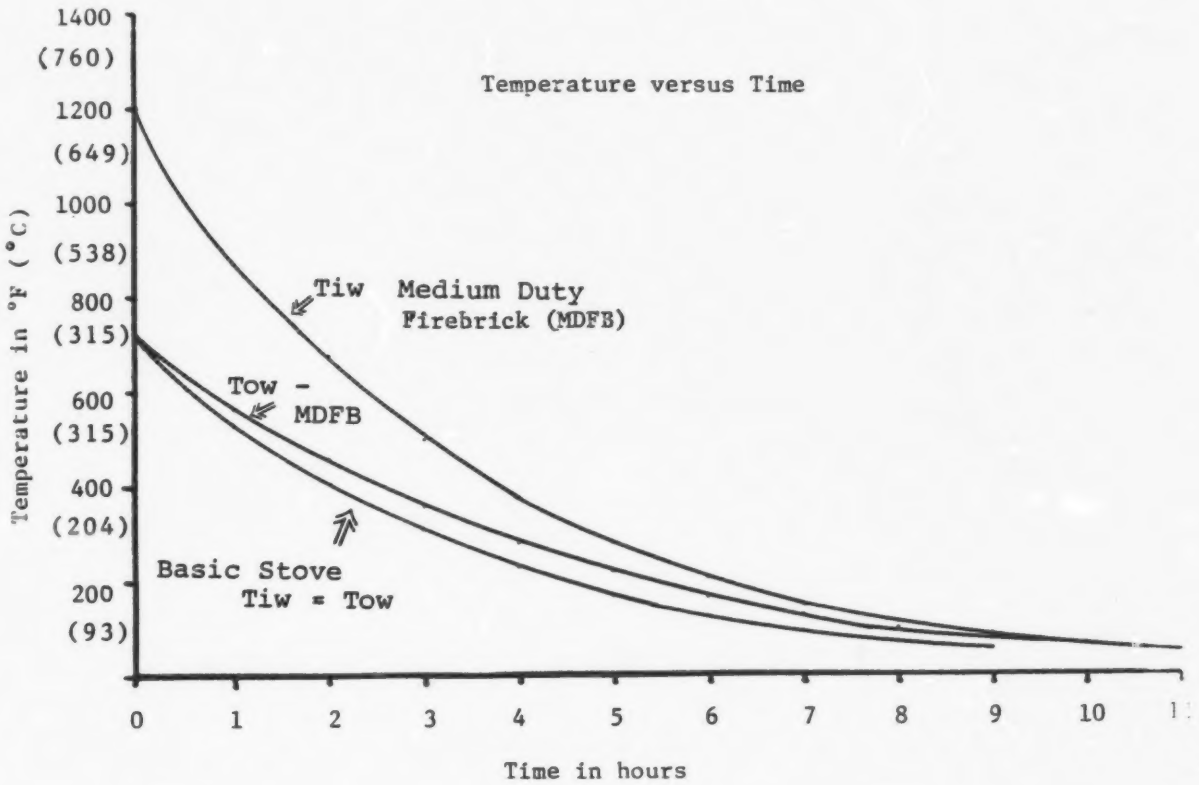

Figure 5-2. Cooldown of a basic wood burning stove (i.e., no insulation and 1/4 inch (0.645 cm) cast iron walls) and an insulated stove (1 inch (2.54 cm) of medium duty firebrick). For the basic stove, inner and outer wall temperatures vary by less than 5 ^{o}F (3^{o}C) so only a single curve is shown. The inner stove wall (Tiw) and outer stove wall (Tow) temperatures are shown for the case of the insulated stove. Initial conditions were set such that the outer wall temperature of the basic stove and the insulated stove were the same.

TABLE 5-3. CALCULATED WALL THICKNESS FOR ASSUMED DESIGN CONDITION OF 1200°F (649°C) INSIDE WALL TEMPERATURE, 720°F (382°C) OUTSIDE WALL TEMPERATURE FOR VARIOUS REFRACTORY MATERIALS

MATERIAL (TRADENAME)	WALL THICKNESS in Inches (cm)
BRICKS	
MDFB	1.0 (2.54)
K23 IFB	0.2 (0.51)
K26 IFB	0.3 (0.76)
K28 IFB	0.3 (0.76)
K30 IFB	0.3 (0.76)
Silica	1.3 (3.30)
HDFB A	1.1 (2.79)
K 3000 IFB	0.3 (0.76)
HDFB B	1.9 (4.83)
Vitrified Silica	0.8 (2.03)
Mullite	1.6 (4.06)
Dense IFB	0.7 (1.78)
Basic (MgO)	2.5 (6.35)
Zircon	2.0 (5.08)
Alumina (90/10)	2.6 (6.60)
Alumina (99/-)	3.2 (8.13)
Silicon Carbide	12.5 (31.75)

(continued)

[NB: NOTES APPEAR AT END OF TABLE.]

TABLE 5-3. (continued)

MATERIAL (TRADENAME)	WALL THICKNESS in Inches (cm)
CASTABLES	
MDFB (brick basis)	1.0 (2.54)
LW 26 (1)	0.1 (0.25)
Kaocrete B (2)	0.5 (1.27)
KS-4 (3)	0.5 (1.27)
Kast-set (3)	0.5 (1.27)
Kaocrete 28 LI (2)	0.7 (1.78)
HW Super Castable (1)	0.8 (2.03)
Visil (1)	0.6 (1.52)
Harchrome (1)	0.8 (2.03)
Hi Alumina (1)	0.9 (2.29)
Alusa (1)	1.2 (3.05)
Castolast G (1)	1.3 (3.30)

NOTES:

(1) Harbison Walker Company.

(2) Babcock & Wilcox - Refractories Division.

(3) A. P. Green Company.

MDFB = Medium-duty firebrick.

IFB = Insulating firebrick.

HDFB = Heavy-duty firebrick.

SECTION 6

RANKING OF CANDIDATE MATERIALS

There are a great many possible ways to rank the numerous candidate materials that exhibit suitable combustion resistance and offer a potential enhancement in combustion efficiency. Logically, the rating criteria of Total Installed Cost (TIC) per unit surface area would be of considerable interest to both wood stove manufacturers and owners. For a given material combination, the TIC for original manufacture could vary considerably from the cost (and practicality) of retrofit. The listing presented in Table VII gives ratios of TIC's, with medium duty fire brick assigned a ratio of 1.0, for new fabrication, using several candidate materials. These TIC's are based on an assumed equivalent temperature profile for the stove wall as described above. It should be noted that the utilization of these potential designs may not prove cost effective compared to the installation of catalytic combustors. The installation of refractory linings may also lead to a higher consumption of fuel per hour.

Several of the castable materials show relatively low TIC's. These values do not, however, consider the potential negative appearance factors and possible cracking common in castable materials.

The light weight insulating bricks and light weight castable materials (densities below approximately 65 pounds per cubic foot (1041 kg/m^3)) also have low TIC's. These materials are very good insulators, therefore, only very thin sections are required to attain an appropriate temperature profile. These insulating refractories are, however, also relatively soft materials. The combination of thin sections and limited strength would tend to make them prone to damage during fuel charging. A composite wall or shield could be used to protect a light weight insulating material.

TABLE 6-1. TOTAL INSTALLED COST (TIC) RATIOS PER UNIT SURFACE AREA FOR VARIOUS REFRACTORY MATERIALS

MATERIAL (TRADENAME)	TIC RATIO *
BRICKS	
MDFB	1.0
K23 IFB	0.5
K26 IFB	1.0
K28 IFB	1.1
K30 IFB	1.3
Silica	1.4
HDFB A	1.5
K 3000 IFB	1.7
HDFB B	5.4
Vitrified Silica	6.5
Mullite	8.8
Dense IFB	9.1
Basic (MgO)	9.4
Zircon	26.9
Alumina (90/10)	35.2
Alumina (99/-)	69.8
Silicon Carbide	438.5

(continued)

[NB: NOTES APPEAR AT END OF TABLE.]

TABLE 6-1. (continued)

MATERIAL (TRADENAME)	TIC RATIO *
CASTABLES	
MDFB (brick basis)	1.0
LW 26 (1)	0.1
Kaocrete B (2)	0.5
KS-4 (3)	0.6
Kast-set (3)	0.6
Kaocrete 28 LI (2)	0.9
HW Super Castable (1)	1.0
Visil (1)	1.4
Harchrome (1)	1.5
Hi Alumina (1)	1.8
Alusa (1)	2.7
Castolast G (1)	7.0

NOTES:

* Ratio of total installed cost per unit of surface area to medium-duty firebrick (MDFB).

(1) Harbison Walker Company.

(2) Babcock & Wilcox - Refractories Division.

(3) A. P. Green Company.

IFB = Insulating firebrick.

HDFB = Heavy-duty firebrick.

SECTION 7.0a

7.0a TWO EXAMPLES OF THE HEAT TRANSFER CALCULATION METHODOLOGY IN ENGLISH UNITS (Examples in metric units are given in Section 7.0b.)

7.1a DEFINITION OF TERMS FOR THE FOLLOWING CALCULATIONS

Basic Stove:

t = time, hrs.

T_{fire} = temperature of firebox gases, °F or °R (°R = °F + 460)

T_w = temperature of Basic Stove wall, °F or °R

$(Q/A)_{fire}$ = heat transferred per square foot of stove wall from the firebox gases, Btu/hrft^2

σ = Stefan - Boltzman constant, Btu/hrft^2°R^4

ε_{fire} = emissivity of firebox gases

α_{fire} = absorptance of firebox gases

$\bar{h}_c$ = average convective conductance, Btu/hrft^2°F

$(Q/A)_{room}$ = heat transferred per square foot of stove wall to the room, Btu/hrft^2

ε = emissivity of cast iron

T_{room} = temperature of the room, °F or °R

Insulated Stove:

T_{iw} = temperature of inner stove wall (insulated wall - firebox side), °F or °R

T_{ow} = temperature of outer stove wall (cast iron - room side), °F or °R

t_{iw} = thickness of insulation, in.

t_{ow} = thickness of cast iron stove wall, in.

k_{iw} = thermal conductivity of insulation, Btu/hrft°F

k_{ow} = thermal conductivity of cast iron, Btu/hrft°F

σ = Stefan-Boltzman constant, Btu/hrft^2°R^4

ε_{fire} = emissivity of firebox gases

α_{fire} = absorptance of firebox gases

$\bar{h}_c$ = average convective conductance, Btu/hrft^2°F

T_{fire} = temperature of firebox gases, °F or °R

$(Q/A)_{fire}$ = heat transferred per square foot of stove wall from firebox gases, Btu/hrft^2

ρ = density of insulation, lb/ft^3

c = specific heat of insulation, Btu/lb°F

T_{av1} = average stove wall temperature (for entire wall, insulation and cast iron) at previous time step, °F

T_{av2} = average stove wall temperature at current time step, °F

$(Q/A)_{wall}$ = heat transferred (per square foot of stove wall) by conduction through the stove wall, Btu/hrft^2

$(Q/A)_{room}$ = heat transferred (per square foot of stove wall) to the room, Btu/hrft^2

ε = emissivity of cast iron

T_{room} = temperature of room, °F or °R

t = time, hr.

7.2a ASSUMPTIONS

Basic Stove:

at t = 0, T_{fire} = 1500°F

at t = 0, T_w = 720°F

at t = 7, T_{fire} = 200°F

$\sigma = 0.171 \times 10^{-8}$ Btu/hrft^2°R^4 (constant)

$\bar{h}_c$ = 2 Btu/hrft^2°F (constant)

ε = 0.875 (constant)

T_{room} = 60°F (constant)

$T_{iw} = T_{ow} = T_w$

Insulated Stove:

at t = 0, T_{ow} = 720°F

at t = 0, T_{iw} = 1200°F

at t = 0, $Q/A_{room\text{-}insulated\ stove} = Q/A_{room\text{-}basic\ stove}$

k_{ow} = 24.8 Btu/hrft°F (constant)

σ = 0.171 X 10^{-8} Btu/hrft^2°R^4 (constant)

$\bar{h}_c$ = 2 Btu/hrft^2°F (constant)

ε = 0.875 (constant)

T_{room} = 60°F (constant)

t_{ow} = 0.25 inch (constant)

Firebox gases, Basic Stove wall, inner and outer insulated stove walls are assumed to cool exponentially, i.e., $T = C_1 e^{\sigma t}$

7.3a EQUATIONS

Governing equations for Basic Stove:

Eq. 1 $(Q/A)_{fire} = \sigma (\varepsilon_{fire} T_{fire}^4 - \alpha_{fire} T_w^4) + \bar{h}_c (T_{fire} - T_w)$

Eq. 2 $(Q/A)_{room} = \sigma\varepsilon (T_w^4 - T_{room}^4) + \bar{h}_c (T_w - T_{room})$

Eq. 3 $(Q/A)_{fire} = (Q/A)_{room}$

Eq. 1 is the heat transferred from the fire gases to the inner stove wall due to radiation (first term) and convective conductance (second term)

Eq. 2 is the heat transferred from the stove wall to the room due to radiation (first term) and convective conductance (second term)

Eq. 3 the heat transferred to the inner wall from the fire is equal to the heat transferred from the outer wall to the room

Insulated Stove:

Eq. 4 $(Q/A)_{fire} = \sigma (\varepsilon_{fire} T_{fire}^4 - \alpha_{fire} T_{iw}^4) + \bar{h}_c (T_{fire} - T_{iw}) + \rho c t_{iw} (T_{av1} - T_{av2})$

Eq. 5 $(Q/A)_{wall} = \dfrac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}}$

Eq. 6 $(Q/A)_{room} = \sigma\varepsilon (T_{ow}^4 - T_{room}^4) + \bar{h}_c (T_{ow} - T_{room})$

Eq. 7 $(Q/A)_{fire} = (Q/A)_{wall} = (Q/A)_{room}$

Eq. 4 is the heat transferred from the firebox gases to the inner stove wall due to radiation (first term), convective conductance (second term), and stored heat in the insulated wall (third term)

Eq. 5 is the heat transferred through the wall due to conduction

Eq. 6 is the heat transferred from the outer stove wall to the room due to radiation and convective conductance

7.4a APPROACH

1. Define firebox and basic stove conditions at time (0). Assume $T_{fire} = 1500°F$ and $T_{room} = 60°F$. Stove is cast iron, uninsulated, and has 1/4 inch wall thickness. Iterating between Eq. 1 and Eq. 2, T_w and $(Q/A)_{fire} = (Q/A)_{room}$ are found, $T_w = 720°F$ and $Q/A = 4063$ Btu/hrft^2.

2. Assume $T_{ow} = 720°F$ is the desired outer wall temperature for an insulated stove at time (0), just as it was for the basic stove at time (0), and that the same heat transfer to the room is desired as with an uninsulated stove, i.e., $Q/A = 4063$ Btu/hrft^2. Assume also that at time (0) it is desired that the inner wall temperature is slightly above the temperature required to combust emission gases, so set $T_{iw} = 1200°F$. Using Eq. 5, the insulation thickness necessary to achieve these conditions can be found. For medium duty firebrick $t_{iw} = 0.914$ inch. Using Eq. 4, T_{fire} at time (0) can also be found (stored energy term is assumed 0) and is $T_{fire} = 1765°F$.

3. The steady-state, time (0) conditions for the firebox gases, Basic Stove and Insulated Stove have now been defined.

4. For cooldown conditions the firebox gases, Basic Stove and Insulated Stove are assumed to cool according to the exponential equation of the form

$$\text{Temp.} = C_1 e^{c\ \text{time}}$$

Using time (0) values found previously for the firebox gas temperatures under Basic Stove and Insulated Stove conditions along with estimated firebox gas temperatures at some later time, cooldown firebox gas temperature profiles can be generated. Using the firebox gas temperature profile, the corresponding wall temperatures can be found by iterating between Eq. 1 and Eq. 2 for the basic stove or Eq. 1, Eq. 2, and Eq. 3 for the Insulated Stove.

5. This method allows a Basic Stove and an Insulated Stove to be compared as both are initially under the same heat transfer to room conditions (i.e., $T_w = T_{ow} = 720°F$ and $Q/A = 4063$ Btu/hrft^2)

7.5a ERROR FACTORS

1.	$\bar{h}_c = 2$ Btu/hrft^2°F	is an estimate and may vary with temperature
2.	$\varepsilon = 0.875$	emissivity varies with temperature. For cast iron, only ranges of emissivity were available, so an averaged value was used and set constant.
3.	ε_{fire} & α_{fire}	emissivity and absorptance vary with fire. Data for CO_2 and water vapor was used; however, data was in graphical format and, therefore, may introduce inaccuracies.
4.	k	thermal conductivity also varies with temperature. Again, ranges were available, so averaged values were used and set constant.
5.	T_{fire}, T_w	initial firebox gas temperature and stove wall temperatures were assumed. While literature supports these values, they are estimates.
6.	Temperature profiles	Again, these are estimates based on literature and experience.

The above error factors may appear cumbersome but the intent of these calculations is not to perfectly describe the heat transfer behavior of the wood burning stoves considered but rather to estimate the trends in the heat transfer behavior.

Error factors 1 through 4 could easily be handled by performing these calculations on a computer where tabular values would be stored and called upon for each iterative step.

Error factors 5 and 6 probably require actual testing to obtain better temperature values.

7.6a BASIC STOVE CALCULATIONS

How does a Basic Stove cool when starting from T_{fire} = 1500°F and T_{wall} = 720°F?

Time t (hrs)	Fire Temp. T_{fire} (°F)	Temp. Stove Wall T_w (°F)
0	1500	(720°F)
1	1125	(545) 544
2	843	(410) 411
3	633	(305) 311
4	474	235
5	356	178
6	267	134
7	200	101

(values in parentheses are calculated values from iteration table below; other values are from exponential cooldown equation)

$$(Q/A)_{fire} = \underbrace{\sigma\,(\varepsilon_{fire}\,T_{fire}^{4} - \alpha_{fire}\,T_{w}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{fire} - T_w)}_{\text{term 2}}$$

$$(Q/A)_{room} = \underbrace{\sigma\varepsilon\,(T_w^{4} - T_{room}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_w - T_{room})}_{\text{term 2}}$$

		$(Q/A)_{fire}$				$(Q/A)_{room}$					
α_{fire}	T_w	term 1	+	term 2	= total	term 1	+	term 2	= total	T_{fire}	ε_{fire}
.15	675	1085	+	900	= 1985	2374	+	1230	= 3604	1125	.14
	600	1187	+	1050	= 2237	1780	+	1080	= 2860		
	550	1244	+	1150	= 2394	1448	+	980	= 2428		
	545	1249	+	1160	= 2409	1417	+	970	= 2387		
	at t = 2, T_{fire} = 843°F									843°F	.15
.18	375	590	+	936	= 1526	618	+	630	= 1248		
	425	550	+	586	= 1136	808	+	730	= 1538		
	400	571	+	886	= 1457	709	+	680	= 1389		
	410	563	+	866	= 1429	748	+	700	= 1448		
	405	567	+	876	= 1443	728	+	690	= 1418		
	at t = 3, T_{fire} = 633°F									633	.15
	275	276	+	716	= 992	327	+	430	= 757		
	300	263	+	666	= 929	390	+	480	= 870		
	325	269	+	616	= 885	459	+	530	= 989		
	305	261	+	656	= 917	403	+	490	= 893		

Basic Stove will cool down exponentially

$$T_w = C_1 e^{ct}$$

$C_1 = 720$ $\quad C = -0.28$

Fire cooldown

$$T_{fire} = C_1 e^{ct}$$

where T_{fire} = 1500°F at t = 0 hrs.

T_{fire} = 200°F at t = 7 hrs.

$C_1 = 1500$ $\quad C = -0.288$

7.7a INSULATED STOVE CALCULATIONS

Given: Medium duty firebrick with $k_{iw} = 0.65$ Btu/hrft°F

$\rho_{iw} = 127$ lb/ft^3

$T_{ow} = 720°F$, $T_{iw} = 1200°F$ } at $t = 0$

$Q/A = 4063$ Btu/hrft^2

What is the insulation thickness for these conditions?

$$Q/A = \frac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}} = \frac{1200 - 720}{t/0.65 + \frac{0.25/12}{24.8}} = 4063$$

$\therefore t = \underline{0.914 \text{ inch}}$

What is the fire temperature necessary for these conditions?

$$Q/A = \sigma (\varepsilon_{fire} T_{fire}^4 - \alpha_{fire} T_{iw}^4) + \bar{h}_c (T_{fire} - T_{iw})$$

$$4063 = 0.171 \times 10^{-8} (0.11 T_{fire}^4 - 0.13 \times 1660°R^4) + 2 (T_{fire} - 1200)$$

try $T_{fire} = 1600°F$

$4063 = 1699 + 800 = 2499$

try $T_{fire} = 1900°F$

$4063 = 4147 + 1400 = 5547$

try $T_{fire} = 1800°F$

$4063 = 3219 + 1200 = 4419$

try $T_{fire} = 1750°F$

$4063 = 2799 + 1100 = 3899$

try $T_{fire} = 1700°F$

$4063 = 2964 + 1140 = 4104$

try $\underline{T_{fire} = 1765°F}$

$4063 = 2922 + 1130 = 4052$

Assume the fire cools exponentially

$$T_{fire} = C_1 e^{ct}$$

and reaches ~200°F in 8 hours

$\underline{C_1 = 1765}$ $\underline{C = -0.27}$

t (hrs)	T_{fire} (°F)	T_{iw} (°F)		T_{ow} (°F)	
0	1765°F	(1200°F)		(720°F)	
1	1347	(876)	898	(570)	
2	1029	(677)	672	(465)	461
3	785	(506)	503	(365)	363
4	599	(380)	376	(285)	285
5	458		281		224
6	349		211		177
7	267		158		139
8	204		118		109
9	155		88		86
10	119		66		68
11	91				
12	69				

(values in parentheses are calculated values for iteration table on next page; other values are from exponential cooldown equation)

Insulated stove will also cool exponentially

$T_{iw} = C_1 e^{ct}$ $\qquad$ $T_{ow} = C_1 e^{ct}$

$C_1 = 1200$ $\qquad$ $C = -0.29$ $\qquad$ $C_1 = 745$ $\qquad$ $C = -0.24$

Insulated Stove

$$(Q/A)_{fire} = \underbrace{\sigma\,(\varepsilon_{fire}\,T_{fire}^{4}) - (\alpha_{fire}\,T_{iw}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{fire} - T_{iw})}_{\text{term 2}} + \underbrace{\rho ct(T_{av_1} - T_{av_2})}_{\text{term 3}}$$

$$(Q/A)_{wall} = \frac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}}$$

$$(Q/A)_{room} = \underbrace{\sigma\varepsilon\,(T_{ow}^{4} - T_{room}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{ow} - T_{room})}_{\text{term 2}}$$

at $t = 1$, $T_{fire} = 1347°F$ $(.11 = \varepsilon_{fire})$

	$(Q/A)_{room}$				$(Q/A)_{fire}$							
T_{ow}	term 1	+	term 2	= total	T_{iw}	α_{fire}	term 1	+	term 2	+	term 3	= total
400	709	+	680	= 1389	564	.15	1724	+	1566	+	925	= 4215
600	1780	+	1080	= 2860	938	.14	1091	+	818	+	370	= 2279
580	1641	+	1040	= 2681	896	.14	1195	+	902	+	429	= 2526
575	1608	+	1030	= 2638	886		1220	+	922	+	444	= 2586
570	1575	+	1020	= 2595	876		1243	+	942	+	459	= 2644
at $t = 2$, $T_{fire} = 1029$ $(.14 = \varepsilon_{fire})$												
420	788	+	720	= 1508	598	.15	855	+	862	+	414	= 2131
450	917	+	780	= 1697	650		787	+	758	+	335	= 1880
470	1010	+	820	= 1830	686		734	+	686	+	281	= 1700
465	986	+	810	= 1796	677		748	+	704	+	294	= 1746
at $t = 3$, $T_{fire} = 785$ $(.15 = \varepsilon_{fire})$												
370	600	+	620	= 1220	514	.15	385	+	542	+	250	= 1177
365	584	+	610	= 1194	506		393	+	558	+	262	= 1213
at $t = 4$, $T_{fire} = 599°F$ (.15)												
270	316	+	420	= 736	357	.16	201	+	484	+	236	= 921
280	339	+	440	= 779	372		192	+	454	+	212	= 858
275	327	+	430	= 757	364		196	+	470	+	224	= 890
285	351	+	450	= 801	380		187	+	438	+	199	= 824
290	365	+	460	= 824	387		182	+	424	+	188	= 794

SECTION 7.0b

7.0 b TWO EXAMPLES OF THE HEAT TRANSFER CALCULATION METHODOLOGY IN METRIC UNITS

7.1 b DEFINITION OF TERMS FOR THE FOLLOWING CALCULATIONS

Basic Stove:

t = time, hrs.

T_{fire} = temperature of firebox gases, °C or °K (°K = °C + 273)

T_w = temperature of Basic Stove wall, °C or °K

$(Q/A)_{fire}$ = heat transferred per square meter of stove wall from the firebox gases, kW/M^2

σ = Stefan - Boltzman constant, $kW/M^2\ °K^4$

ε_{fire} = emissivity of firebox gases

α_{fire} = absorptance of firebox gases

$\bar{h}_c$ = average convective conductance, $kW/M^2\ °C$

$(Q/A)_{room}$ = heat transferred per square meter of stove wall to the room, kW/M^2

ε = emissivity of cast iron

T_{room} = temperature of the room, °C or °K

Insulated Stove:

T_{iw} = temperature of inner stove wall (insulated wall - firebox side), °C or °K

T_{ow} = temperature of outer stove wall cast iron - room side), °C or °K

t_{iw} = thickness of insulation, cm

t_{ow} = thickness of cast iron stove wall, cm

k_{iw} = thermal conductivity of insulation, W/M °C

k_{ow} = thermal conductivity of cast iron, W/M °C

σ = Stefan-Boltzman constant, $kW/M^2\ °K^4$

ε_{fire} = emissivity of firebox gases

α_{fire} = absorptance of firebox gases

$\bar{h}_c$ = average convective conductance, $kW/M^2\ °C$

T_{fire} = temperature of firebox gases, °C or °K

$(Q/A)_{fire}$ = heat transferred per square foot of stove wall from firebox gases, kW/M^2

ρ = density of insulation, Kg/M^3

c = specific heat of insulation, kJ/kg °C

T_{av1} = average stove wall temperature (for entire wall, insulation and cast iron) at previous time step, °C

T_{av2} = average stove wall temperature at current time step, °C

$(Q/A)_{wall}$ = heat transferred (per square meter of stove wall) by conduction through the stove wall, kW/M^2

$(Q/A)_{room}$ = heat transferred (per square meter of stove wall) to the room, kW/M^2

ε = emissivity of cast iron

T_{room} = temperature of room, °C or °K

t = time, hr.

7.2 b ASSUMPTIONS

Basic Stove:

at t = 0, T_{fire} = 816 °C

at t = 0, T_w = 382°C

at t = 7, T_{fire} = 93°C

$\sigma = 5.67 \times 10^{-11}$ $kW/M^2\ °K^4$ (constant)

$\overline{h}_c = 1.1 \times 10^{-2}$ kW/M^2 °C (constant)

ε = 0.875 (constant)

T_{room} = 16 °C (constant)

$T_{iw} = T_{ow} = T_w$

Insulated Stove:

at t = 0, T_{ow} = 382°C

at t = 0, T_{iw} = 649 °C

at t = 0, $Q/A_{room\text{-}insulated\ stove} = Q/A_{room\text{-}basic\ stove}$

k_{ow} = 42.9 w/M°C (constant)

σ = 5.67 x 10^{-11} kW/M^2 °K^4 (constant)

$\bar{h}_c$ = 1.1 x 10^{-2} kW/M^2 °C (constant)

ε = 0.875 (constant)

T_{room} = 16 °C (constant)

t_{ow} = 0.64 cm. (constant)

Firebox gases, Basic Stove wall, inner and outer insulated stove walls are assumed to cool exponentially, i.e., $T = C_1 e^{ct}$

7.3b EQUATIONS

Governing equations for Basic Stove:

Eq. 1 $(Q/A)_{fire} = \sigma (\varepsilon_{fire} T_{fire}^4 - \alpha_{fire} T_w^4) + \bar{h}_c (T_{fire} - T_w)$

Eq. 2 $(Q/A)_{room} = \sigma\varepsilon (T_w^4 - T_{room}^4) + \bar{h}_c (T_w - T_{room})$

Eq. 3 $(Q/A)_{fire} = (Q/A)_{room}$

Eq. 1 is the heat transferred from the fire gases to the inner stove wall due to radiation (first term) and convective conductance (second term)

Eq. 2 is the heat transferred from the stove wall to the room due to radiation (first term) and convective conductance (second term)

Eq. 3 the heat transferred to the inner wall from the fire is equal to the heat transferred from the outer wall to the room

Insulated Stove:

Eq. 4 $(Q/A)_{fire} = \sigma (\varepsilon_{fire} T_{fire}^4 - \alpha_{fire} T_{iw}^4) + \bar{h}_c (T_{fire} - T_{iw}) + \rho c t_{iw} (T_{av1} - T_{av2})$

Eq. 5 $(Q/A)_{wall} = \dfrac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}}$

Eq. 6 $(Q/A)_{room} = \sigma\varepsilon (T_{ow}^4 - T_{room}^4) + \bar{h}_c (T_{ow} - T_{room})$

Eq. 7 $(Q/A)_{fire} = (Q/A)_{wall} = (Q/A)_{room}$

Eq. 4 is the heat transferred from the firebox gases to the inner stove wall due to radiation (first term), convective conductance (second term), and stored heat in the insulated wall (third term)

Eq. 5 is the heat transferred through the wall due to conduction

Eq. 6 is the heat transferred from the outer stove wall to the room due to radiation and convective conductance

7.4 b APPROACH

1. Define firebox and basic stove conditions at time (0). Assume $T_{fire} = 816^{\circ}C$ and $T_{room} = 16^{\circ}C$. Stove is cast iron, uninsulated, and has 0.64 cm wall thickness. Iterating between Eq. 1 and Eq. 2, T_w and $(Q/A)_{fire} = (Q/A)_{room}$ are found, $T_w = 382^{\circ}C$ and $Q/A = 12.8\ kW/M^2$

2. Assume $T_{ow} = 382^{\circ}C$ is the desired outer wall temperature for an insulated stove at time (0), just as it was for the basic stove at time (0), and that the same heat transfer to the room is desired as with an uninsulated stove, i.e., $Q/A = 12.8\ kW/M^2$. Assume also that at time (0) it is desired that the inner wall temperature is slightly above the temperature required to combust emission gases, so set $T_{iw} = 649^{\circ}C$. Using Eq. 5, the insulation thickness necessary to achieve these conditions can be found. For medium duty firebrick $t_{iw} = 2.32$ cm. Using Eq. 4, T_{fire} at time (0) can also be found (stored energy term is assumed 0) and is $T_{fire} = 963\ ^{\circ}C$

3. The steady-state, time (0) conditions for the firebox gases, Basic Stove and Insulated Stove have now been defined.

4. For cooldown conditions the firebox gases, Basic Stove and Insulated Stove are assumed to cool according to the exponential equation of the form

$$\text{Temp.} = C_1 e^{c\ \text{time}}$$

Using time (0) values found previously for the firebox gas temperatures under Basic Stove and Insulated Stove conditions along with estimated firebox gas temperatures at some later time, cooldown firebox gas temperature profiles can be generated. Using the firebox gas temperature profile, the corresponding wall temperatures can be found by iterating between Eq. 1 and Eq. 2 for the basic stove or Eq. 1, Eq. 2, and Eq. 3 for the Insulated Stove.

5. This method allows a Basic Stove and an Insulated Stove to be compared as both are initially under the same heat transfer to room conditions (i.e., $T_w = T_{ow} = 382\,^{\circ}C$ and $Q/A = 12.8\ kW/M^2$)

7.5 b ERROR FACTORS

1. $\bar{h}_c = 1.1 \times 10^{-2}\ kW/M^2\ ^{\circ}C$ is an estimate and may vary with temperature

2. $\varepsilon = 0.875$ — emissivity varies with temperature. For cast iron, only ranges of emissivity were available, so an averaged value was used and set constant.

3. ε_{fire} & α_{fire} — emissivity and absorptance vary with fire. Data for CO_2 and water vapor was used; however, data was in graphical format and, therefore, may introduce inaccuracies.

4. k — thermal conductivity also varies with temperature. Again, ranges were available, so averaged values were used and set constant.

5. T_{fire}, T_w — initial firebox gas temperature and stove wall temperatures were assumed. While literature supports these values, they are estimates.

6. Temperature profiles — Again, these are estimates based on literature and experience.

The above error factors may appear cumbersome but the intent of these calculations is not to perfectly describe the heat transfer behavior of the wood burning stoves considered but rather to estimate the trends in the heat transfer behavior.

Error factors 1 through 4 could easily be handled by performing these calculations on a computer where tabular values would be stored and called upon for each iterative step.

Error factors 5 and 6 probably require actual testing to obtain better temperature values.

7.6 b BASIC STOVE CALCULATIONS

How does a Basic Stove cool when starting from T_{fire} = 816 °C

T_{wall} = 382 °C

Time	Fire Temp.	Temp. Stove Wall		
t (hrs)	T_{fire} (°C)	T_w (°C)		(values in parentheses are calculated values from iteration table below; other values are from exponential cooldown equation)
0	816	(382)	284	
1	607	(285)	211	
2	451	(210)	155	
3	334	(152)	113	
4	246		81	
5	180		57	
6	131		38	
7	93			

$$(Q/A)_{fire} = \underbrace{\sigma\,(\varepsilon_{fire}\,T_{fire}^{4} - \alpha_{fire}\,T_w^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{fire} - T_w)}_{\text{term 2}}$$

$$(Q/A)_{room} = \underbrace{\sigma\varepsilon\,(T_w^{4} - T_{room}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_w - T_{room})}_{\text{term 2}}$$

		$(Q/A)_{fire}$					$(Q/A)_{room}$						
α_{fire}	T_w	term 1	+	term 2	=	total	term 1	+	term 2	=	total	T_{fire}	ε_{fire}
0.15	357	3.4	+	2.8	=	6.2	7.5	+	3.9	=	11.4	607°C	.14
	316	3.7	+	3.3	=	7.0	5.6	+	3.4	=	9.0		
	288	3.9	+	3.6	=	7.5	4.6	+	3.1	=	7.7		
	285	3.9	+	3.7	=	7.6	4.5	+	3.1	=	7.6		
at t = 2, T_{fire} = 451°C												451 C	.15
0.18	191	1.8	+	3.0	=	4.8	1.9	+	2.0	=	3.9		
	218	1.7	+	1.8	=	3.5	2.5	+	2.3	=	4.8		
	204	1.8	+	2.8	=	3.6	2.2	+	2.1	=	4.3		
	210	1.8	+	2.7	=	4.5	2.4	+	2.2	=	4.6		
	207	1.8	+	2.8	=	4.6	2.3	+	2.2	=	4.5		
at t = 3, T_{fire} = 334°C												334°C	.15
	135	0.9	+	2.3	=	3.2	1.0	+	1.4	=	2.4		
	149	0.8	+	2.1	=	3.1	1.2	+	1.5	=	2.7		
	163	0.8	+	1.9	=	2.7	1.4	+	1.7	=	3.1		
	152	0.8	+	2.1	=	2.9	1.3	+	1.5	=	2.8		

Basic Stove will cool down exponentially

$$T_w = C_1 e^{ct}$$

$C_1 = 382$ $\quad C = -0.28$

Fire cooldown

$$T_{fire} = C_1 e^{ct}$$

where $T_{fire} = 816°C$ at $t = 0$ hrs.

$T_{fire} = 93°C$ at $t = 7$ hrs.

$C_1 = 816$ $\quad C = -0.288$

7.7 b INSULATED STOVE CALCULATIONS

Given: Medium duty firebrick with $k_{iw} = 1.1$ W/M °C

$\rho_{iw} = 2.0$ kg/M^3

$T_{ow} = 382$ °C
$T_{iw} = 649$ °C
} at t = 0

$Q/A = 12.8$ kW/M^2 °C

What is the insulation thickness for these conditions?

$$Q/A = \frac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}} = \frac{649 - 382}{t/1.1 + \frac{0.64}{42.9}} = 12.8$$

$\therefore$ t = 2.3 cm

What is the fire temperature necessary for these conditions?

$$Q/A = \sigma (\varepsilon_{fire} T_{fire}^4 - \alpha_{fire} T_{iw}^4) + \bar{h}_c (T_{fire} - T_{iw})$$

$$12.8 = 5.67 \times 10^{-11} (0.11 T_{fire}^4 - 0.13 \times 922\ °K^2) + 2 (T_{fire} - 649$$

try $T_{fire} = 871$°C

12.8 = 5.3 + 2.5 = 7.8

try $T_{fire} = 1038$ °C

12.8 = 13.1 + 4.4 = 17.5

try $T_{fire} = 982$ °C

12.8 = 10.2 + 3.8 = 14.0

try $T_{fire} = 954$ °C

12.8 = 8.8 + 3.5 = 12.3

try $T_{fire} = 927$ °C

12.8 = 9.4 + 3.6 = 13.0

try $T_{fire} = 963$ °C

12.8 = 9.2 + 3.6 = 12.8

Assume the fire cools exponentially

$$T_{fire} = C_1 e^{ct}$$

and reaches 93 C in 8 hours

$C_1 = 96.3$ $\quad$ $C = -0.27$

t (hrs)	T_{fire} (°C)	T_{iw} (°C)		T_{ow} (°C)	
0	963	(649)		(382)	
1	731	(469)		(300)	
2	554	(358)	356	(241)	238
3	418	(263)	262	(185)	184
4	315	(193)	191	(141)	141
5	237		138		107
6	176		99		81
7	131		70		59
8	96		48		43
9	68		31		30
10	48		19		20
11	33				
12	21				

(values in parentheses are calculated values for iteration table on next page; other values are from exponential cooldown equation)

Insulated stove will also cool exponentially

$T_{iw} = C_1 e^{ct}$ $T_{ow} = C_1 e^{ct}$

$C_1 = 649$ $C = -0.29$ $C_1 = 396$ $C = -0.24$

Insulated Stove

$$(Q/A)_{fire} = \underbrace{\sigma\,(\varepsilon_{fire}\,T_{fire}^{4}) - (\alpha_{fire}\,T_{iw}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{fire} - T_{iw})}_{\text{term 2}} + \underbrace{\rho ct(T_{av1} - T_{av2})}_{\text{term 3}}$$

$$(Q/A)_{wall} = \frac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}}$$

$$(Q/A)_{room} = \underbrace{\sigma\varepsilon\,(T_{ow}^{4} - T_{room}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{ow} - T_{room})}_{\text{term 2}}$$

at t = 1, T_{fire} = 731 °C (.11 = ε_{fire})

	$(Q/A)_{room}$					$(Q/A)_{fire}$			
T_{ow}	term 1 + term 2	= total	T_{iw}	α_{fire}	term 1 + term 2 + term 3	= total
204	2.2 + 2.1	= 4.3	296	0.15	5.4 + 4.9 + 2.9	= 13.2
316	5.6 + 3.4	= 9.0	503	0.14	3.4 + 2.6 + 1.2	= 7.2
304	5.2 + 3.3	= 8.5	480	0.14	3.8 + 2.8 + 1.4	= 8.0
302	5.1 + 3.2	= 8.3	474		3.8 + 2.9 + 1.4	= 8.1
299	5.0 + 3.2	= 8.2	469		3.9 + 3.0 + 1.4	= 8.3
at t = 2, T_{fire} = 554 °C (0.14 = ε_{fire})						
216	2.5 + 2.3	= 4.8	314	0.15	2.7 + 2.7 + 1.3	= 6.7
232	2.9 + 2.5	= 5.4	343		2.5 + 2.4 + 1.1	= 6.0
243	3.2 + 2.6	= 5.8	363		2.3 + 2.2 + 0.9	= 5.4
241	3.1 + 2.6	= 5.7	358		2.4 + 2.2 + 0.9	= 5.3
at t = 3, T_{fire} = 418 °C (0.15 = ε_{fire})						
188	1.9 + 2.0	= 3.9	268	0.15	1.2 + 1.7 + 0.8	= 3.7
185	1.8 + 1.9	= 3.7	263		1.2 + 1.8 + 0.8	= 3.8
at t = 4, T_{fire} = 315°C (0.15 = ε_{fire})						
132	1.0 + 1.3	= 2.3	181	0.16	0.6 + 1.5 + 0.7	= 2.8
138	1.1 + 1.4	= 2.5	189		0.6 + 1.4 + 0.7	= 2.7
135	1.0 + 1.4	= 2.4	184		0.6 + 1.5 + 0.7	= 2.8
141	1.1 + 1.4	= 2.5	193		0.6 + 1.4 + 0.6	= 2.6
143	1.2 + 1.5	= 2.7	197		0.6 + 1.3 + 0.6	= 2.5